Rock varnish evidence for latest Pleistocene millennial-scale wet events in the drylands of western United States

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ABSTRACT

Rock varnish from late to latest Pleistocene geomorphic features in the drylands of the western U.S. provides evidence of nine millennial-scale wet events from 11,500–18,000 calendar yr B.P., represented by regionally replicable and approximately evenly spaced manganese- and barium-rich dark bands in varnish microstratigraphy. Preliminary radiometric age calibration indicates that these events appear to be broadly coeval with millennial-scale cooling events identified in the Greenland Ice Sheet Project 2 (GISP2) ice core record. Six of these wet events are associated with the cold intervals of the Younger Dryas and Heinrich event H1, and the other three with the short-lived cooling phases of the Intra-Allerød Cold Period, the Older Dryas, and the Oldest Dryas. These results, combined with our previous documentation of millennial-scale wet events in the Holocene varnish record for the same region, indicate that such wet oscillations in the western U.S. may be parts of regionally widespread manifestation of well-documented, pervasive millennial-scale cycles of the North Atlantic climate.

Keywords: rock varnish, wet events, cooling events, Younger Dryas, Heinrich events, western U.S.

INTRODUCTION

Obtaining continuous millennial-scale climate records for the world's deserts has proven to be a difficult, but often critical step in understanding the mechanism and spatial variations of Earth's climate. Evidence for such short-term climate changes in deserts is rare and has come principally from pollen records and from lake and cave deposits (e.g., Davis, 1992; Allen and Anderson, 2000; Polyak et al., 2004). Here we report rock varnish evidence for latest Pleistocene (11,500–18,000 yr B.P.; in calendar yr B.P. unless noted otherwise) millennial-scale wet events in the drylands of western U.S.

Rock varnish is a slowly accreting (<1–40 µm/k.y.) dark coating on subaerially exposed rock surfaces, most commonly in arid to semiarid deserts. Because of its sedimentary origin, varnish often displays layered microstratigraphy. Previous studies (Dorn, 1990; Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001; Lee and Bland, 2003) revealed that the chemical composition of varnish microstratigraphy changes markedly with climate: dry periods generate Mn- and Ba-poor layers while wet periods produce Mn- and Ba-rich microlaminae. Such climate-related microstratigraphy in varnish can be correlated across a given geographic region, suggesting that the climate signals recorded in varnish are of regional extent (Liu and Dorn, 1996; Liu et al., 2000). In the Great Basin of the western U.S., Mn- and Ba-poor varnish layers, which are yellow in ultrathin sections (~5–10 µm thick) under transmitted light, formed during the current, unusually dry interglacial of the Holocene; Mn- and Ba-rich dark layers were deposited during the last glaciation when the Great Basin was much wetter than at present (Broecker and Liu, 2001). A recent study (Liu, 2003) demonstrated that wet events represented by the glacial-age dark layers correlate in time with cold episodes of the Younger Dryas and Heinrich events H1–H6 in the North Atlantic region. Our new study (Liu and Broecker, 2007) shows that the Holocene wet events recorded in varnish are likewise contemporaneous with Holocene millennial-scale cooling events in the North Atlantic (Bond et al., 1997).

METHODS

In a search for rock varnish evidence of latest Pleistocene millennial-scale wet events in the western U.S. drylands, we collected relatively fast accreting varnish samples from a number of late to latest Pleistocene geomorphic features (Table 1). These features include alluvial fan surfaces in Death Valley, California (CA); Lone Pine fault scarp and Owens River dry falls in Owens Valley, CA; highstand shorelines of Silver Lake and Coyote Lake, CA; Provo shorelines of Bonneville Lake, Utah; highstand shorelines of Summer Lake, Oregon; and alluvial terraces in the Ajo Mountains, Arizona. Many of these geomorphic features have been well dated by ^{14}C or cosmogenic radionuclide methods, thus providing preliminary age calibration of millennial-scale wet events recorded in varnish microstratigraphy (Table 1).

A key to this study is an innovative method of making ultrathin sections (5–10 µm thick) of rock varnish (Liu and Dorn, 1996) that reduces failure rates from 80% to <5% and permits rapid

TABLE 1. ROCK VARNISH SAMPLE LOCATIONS, GEOMORPHIC CONTEXT, AND AGE CONSTRAINTS

	Sample site and geomorphic context	Estimated or reported age	Calibrated calendar age*	Age used for calibration§	Age type and source
Figure 1					
A, B	Mormon Point fan, DV (CA)	Latest Pleistocene			Geomorphic age (this study)
C	Anvil Canyon fan, DV (CA)	Latest Pleistocene			Geomorphic age (this study)
D	Summer Lake SL (OR)	Latest Pleistocene			Geomorphic age (this study)
Figures 2 and 3					
A	Silver Lake SL (CA)	10,500–15,000	12,380 ± 290†	12,180 ± 290	^{14}C (Wells et al., 1987)
B	Coyote Lake SL (CA)	11,360 ± 340	13,220 ± 330	13,020 ± 330	^{14}C (Meek, 1990)
C	Dry Falls, OV (CA)	ca. 15,900	ca. 15,900	ca. 15,700	^{3}He (Cerling, 1990)
D	Bonneville Lake SL, TH (UT)	14,400 ± 100	16,960 ± 200	16,760 ± 200	^{14}C (Cerling, 1990)
E	Lone Pine fault scarp, OV (CA)	ca. 17,400	ca. 17,400	ca. 17,200	^{10}Be (Bierman et al., 1995)
F	Organ Pipe alluvial terrace (AZ)	14,880 ± 70	17,860 ± 200	17,660 ± 200	^{14}C (Pohl, 1995)

Note: All ages are reported in yr B.P., with 1σ age uncertainties if applicable.
DV—Death Valley; OV—Owens Valley; SL—shorelines; TH—Tabernacle Hills; AZ—Arizona; CA—California; OR—Oregon; UT—Utah.
*The calibrated ^{14}C ages are obtained via the Fairbanks et al. (2005) calibration program (version: Fairbanks0107) and rounded up to the nearest 10.
†The minimum ^{14}C age of 10,500, with assumed 1σ age uncertainties of ±200 yr, is used for calibration.
§Given a lag time of ~200 yr for the varnish initiation on subaerially exposed rock surfaces, ages used for calibration of the varnish layering sequence in this study are calculated as "calibrated age minus 200 yr."

preparation and thus intercomparison of many sections. The conventional way of making thin sections cannot be employed because the resulting thin sections are too thick (25–30 µm) and do not reveal the microstratigraphy.

Once the ultrathin sections were prepared, they were photographed using a Leica DMLB polarized light microscope equipped with a Leica MPS 60 Photoautomat system, yielding high-resolution (~1 µm) images of varnish microstratigraphy for layering pattern analysis. Ultrathin sections that contain clearly defined varnish microstratigraphies were selected for further chemical analyses with a fully automated five-spectrometer CAMECA SX100 electron probe. Probe X-ray line profiling provides high-resolution (~2 µm) chemical varnish microstratigraphy. A combination of both optical and chemical microstratigraphy allows detailed detection of Mn, Ba, and other elemental fluctuations in varnish.

In this study, we collected 38 varnish samples from 10 different localities in the drylands of western U.S. We made a total of 147 ultrathin sections, and 650 spot chemical measurements were obtained by electron microprobe along 8 individual line profiles. These chemical data, together with more than 200 high-resolution (~1 µm) optical images of varnish microstratigraphy, form the database used to generalize and correlate varnish layering sequences.

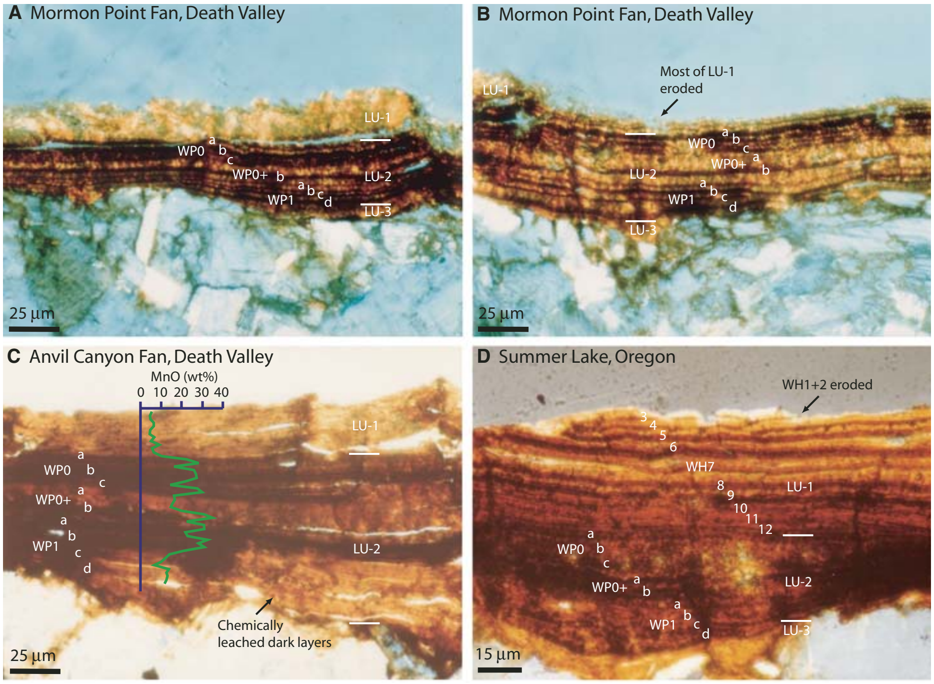

Figure 1. Regionally replicable latest Pleistocene varnish microstratigraphies from western U.S. Mn-rich dark bands in images represent periods of wet climate during latest Pleistocene; Mn-poor surface yellow layers in A and C represent periods of Holocene dry climate. Note that one section in D contains 10 weak dark layers in upper portion of varnish microstratigraphy (LU-1), indicative of Holocene wet events. Also note that, due to postdepositional chemical leaching, Mn-rich dark bands WP1b–WP1d in C have been partially altered into Mn-intermediate orange layers, as revealed by microprobe line profile analyses. LU—layering unit; WH—wet event in Holocene; WP—wet event in Pleistocene.

RESULTS

By selecting fine-grained (<0.1 µm) and fast-accreting (5–15 µm/k.y.) varnish and by making slightly thinner (<5–10 µm) varnish ultrathin sections, we were able to detect and assess narrowly spaced varnish microlamination signals of latest Pleistocene wet events in the study region. In Death Valley, varnish from latest Pleistocene fan surfaces at Mormon Point displays nine nearly evenly spaced narrow dark bands within the LU-2 chronozone (Figs. 1A, 1B). Here, LU-2 refers to "layering unit 2" in a generalized late Pleistocene varnish microstratigraphy for the western U.S. drylands and represents the time span of ca. 11,500–18,000 yr B.P. (Fig. 2; Liu, 2003). Similar layering sequences were observed in varnish from Anvil Canyon fan surfaces in Death Valley and from the highstand shorelines of Summer Lake in Oregon (Figs. 1C, 1D).

After examination of hundreds of individual varnish microbasins (1–3-mm-wide, <1-mm-deep varnish-filled microdepressions on rock surfaces) from the study region, we established a generalized latest Pleistocene layering sequence in varnish (Fig. 2). This sequence contains nine approximately evenly spaced dark bands (each ~1–8 µm thick) intercalated with eight orange bands (each ~1–5 µm thick). Three of these dark bands, WP0a, WP0b, and WP0c, occur within the upper portion of the sequence (WP0), two (WP0+a, WP0+b) within the middle portion (WP0+), and four (WP1a, WP1b, WP1c, WP1d) within the lower portion of the sequence (WP1). Here, WP stands for "wet event in Pleistocene"; WP0 and WP1 represent two major dark layers, and WP0+ represents one major orange layer in the LU-2 chronozone. Electron microprobe chemical analyses indicate that these dark bands are enriched in Mn and Ba (usually containing 25%–45% MnO and 1%–4% BaO), and orange bands are relatively depleted in Mn and Ba (usually containing 15%–25% MnO and 1%–2% BaO) (Figs. 1C and 3A). As documented in our previous studies (Liu et al., 2000; Broecker and Liu, 2001; Liu, 2003), these Mn- and Ba-rich dark bands represent periods of wet climate during the latest Pleistocene in the western U.S. drylands.

Preliminary radiometric age calibration of varnish microstratigraphy provides constraints on the timing of these wet events. Varnish samples from the ^{14}C-dated highstand shorelines of Silver Lake (12,380 ± 290 yr B.P.; Wells et al., 1987) and Coyote Lake (13,220 ± 330; Meek, 1990) display layering sequences LU-1/LU-2 (WP0b) and LU-1/LU-2 (WP0c), respectively (Figs. 3A, 3B). Here LU-1/LU-2 (WP0b) stands for a layering sequence LU-1/LU-2 with basal layer WP0b, and LU-1/LU-2 (WP0c) with basal layer WP0c. If the lag time of varnish initiation on subaerially exposed rocks from these shorelines is assumed to be ~200 yr (Liu and Broecker, 2007), the basal dark layers WP0b and WP0c in the varnish microbasins were likely deposited during wet periods ca. 12,180 ± 290 and 13,020 ± 330 yr B.P., respectively. Similarly, varnish samples from the ^{3}He-dated Owens Valley dry falls (ca. 15,900 yr B.P.; Cerling, 1990), the ^{14}C-dated Provo shorelines of Bonneville Lake at Tabernacle Hills (16,960 ± 200 yr B.P.; Cerling, 1990), and the ^{10}Be-dated Lone Pine fault scarp (ca. 17,400 yr B.P.; Bierman et al., 1995) display layering sequences LU-1/LU-2 (WP1a), LU-1/LU-2 (WP1b), and LU-1/LU-2 (WP1c), respectively, suggesting that dark bands WP1a, WP1b, and WP1c in these varnish microbasins were deposited during wet periods ca.15,700, 16,760 ± 200, and 17,200 yr B.P., respectively (Figs. 3C–3E). Further, varnish from ^{14}C-dated alluvial terraces in the Ajo Mountains (17,860 ± 200 yr B.P.; Pohl, 1995) displays layering sequence LU-1/LU-2 (WP1d), indicating that the basal dark layer WP1d in the varnish was formed during a wet period ca. 17,660 ± 200 yr B.P. (Fig. 3F). Figure 2 gives a graphic summary of the above radiometric age calibration.

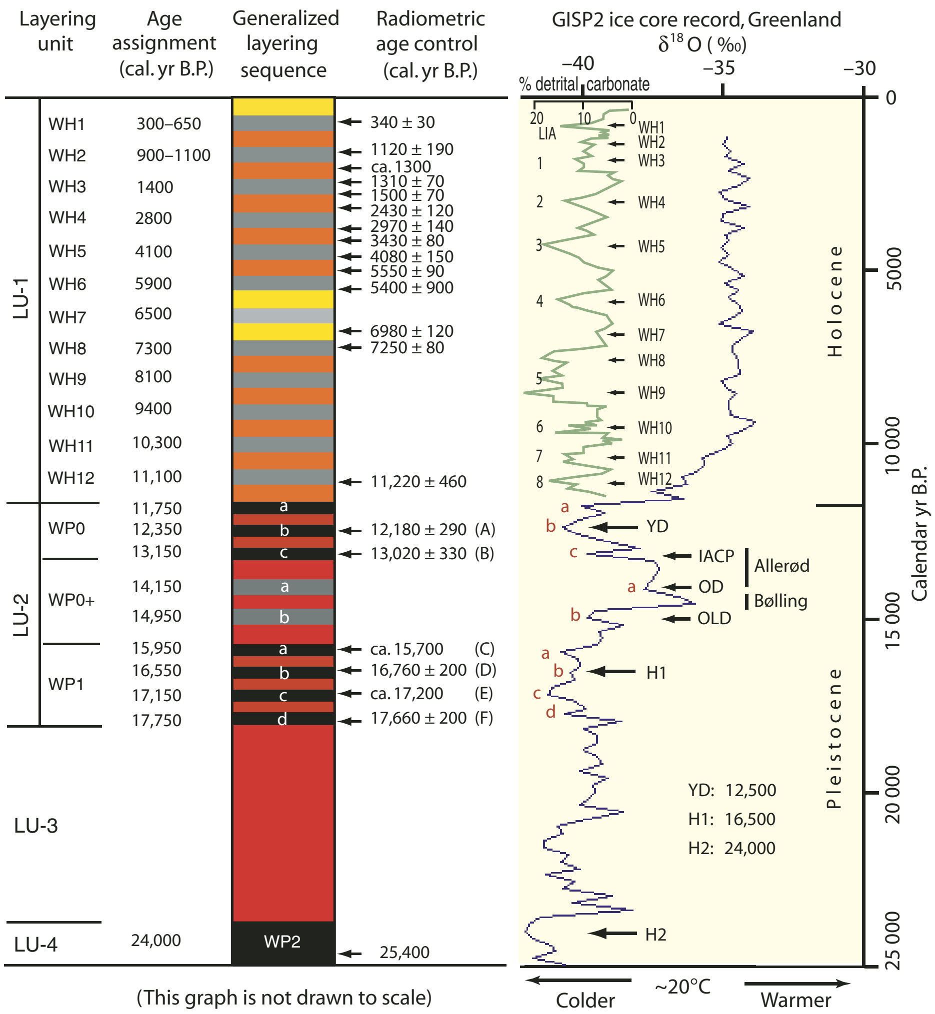

Figure 2. Generalized latest Pleistocene varnish layering sequence for western U.S. and its radiometric age calibration and climatic correlation with the 200 yr smoothed Greenland Ice Sheet Project 2 (GISP2) ice core record (Alley et al., 1993). Wet events recorded as dark layers (WP0a–WP0c, WP0+a, WP0+b, and WP1a–WP1d) in the varnish layering sequence closely correlate with cooling events represented by oxygen isotopic troughs (labeled a, b, c, d) in the GISP2 record. Also included in this diagram are radiometric age calibration and climatic correlation of Holocene wet events (WH1–WH12) in the varnish record (Liu and Broecker, 2007) with the Holocene cooling events (LIA, 1–8) in North Atlantic deep-sea sediment records (Bond et al., 1997). Age constraints are reported in calendar yr B.P. (±1σ if applicable) and letters are keyed to those in Figure 3 and Table 1. Age assignments for dark layers in the varnish record are derived from climatic correlation (rounded to nearest 50 yr). LIA—Little Ice Age; H—Heinrich event; YD—Younger Dryas; IACP—Intra-Allerød Cold Period; OD—Older Dryas; OLD—Oldest Dryas.

DISCUSSION

Based on the above preliminary age calibration of the generalized varnish layering sequence, we found a correlation between the latest Pleistocene millennial-scale wet events recorded in the varnish and the millennial-scale cooling events recorded in the Greenland Ice Sheet Project 2 (GISP2) ice core (Fig. 2). Several lines of evidence support such correlation. First, a close match in the number of wet events and cold events exists between the two climate records. During the latest Pleistocene of 11,500–18,000 yr B.P., a total of nine cooling events (each represented by an oxygen isotopic trough labeled as a, b, c, or d) can be recognized in the 200 yr smoothed GISP2 ice core record. Within the first order of approximation, these nine cooling events probably match the nine wet events uncovered in the varnish record (Fig. 2).

Second, a close match in the timing of wet events and cold events exists between the two climate records. According to our preliminary radiometric age calibration, wet events WP0b and WP0c in the varnish record occurred ca. 12,180 ± 290 and 13,020 ± 330 yr B.P., respectively, which agrees well with the timing of the early phase of the Younger Dryas (12,350 yr B.P.) and the Intra-Allerød Cold Period (13,150 yr B.P.). Similarly, wet events WP1a, WP1b, WP1c, and WP1d in the varnish record occurred ca. 15,700, 16,760 ± 200, 17,200, and 17,660 ± 200 yr B.P., respectively, closely correlating with four cooling pulses ca. 15,950, 16,550, 17,150, and 17,750 yr B.P. during the cold interval of Heinrich event H1. Wet events WP0a, WP0+a, and WP0+b are likely tied to the terminal phase of the Younger Dryas (11,750 yr B.P.), the Older Dryas (14,150 yr B.P.), and the Oldest Dryas (14,950 yr B.P.) (Fig. 2), respectively, but more radiometric age calibration is needed to confirm this correlation.

Third, a similar correlation of wet events with cold events appears to hold between the two geographic regions during both the Holocene and the last glacial time. Bond et al. (1997) discovered a pervasive millennial-scale cycle in the North Atlantic Holocene and glacial climates. The Holocene portion of these climate cycles contains a total of nine cooling events, the most recent being the Little Ice Age (LIA). We (Liu and Broecker, 2007) have shown that, as depicted in Figure 2, these Holocene cooling events correlate closely with the Holocene millennial-scale wet events recorded in varnish from the western U.S. drylands. Such correlation also exists between glacial-age wet events WP2–WP6 in the varnish record and Heinrich events H2–H6 in North Atlantic deep-sea sediment records (Liu and Dorn, 1996; Liu, 2003). By the same reasoning, the latest Pleistocene millennial-scale wet events and cold events should correlate in the same fashion between the two regions. These results further indicate that the millennial-scale wet events recorded in varnish may be parts of regionally widespread manifestation of well-documented, pervasive millennial-scale cooling cycles in the North Atlantic Holocene and glacial climates (Fig. 2).

CONCLUSION

Rock varnish in the western U.S. drylands recorded latest Pleistocene millennial-scale wet events that largely correlate in time with millennial-scale cooling events in the GISP2 ice core record. This finding constitutes new convincing evidence that the millennial-scale wet events recorded in varnish may be parts of regionally widespread manifestation of the pervasive millennial-scale cooling cycles recognized in the North Atlantic Holocene and glacial climates. This finding further demonstrates the great potential that varnish microstratigraphy has for use as a unique paleoenvironmental research tool to reconstruct the climatic history of the world's deserts. Because climatic signals recorded in varnish are regionally synchronous, the radiometrically calibrated and climatically correlated millennial-scale varnish microstratigraphy obtained in this study may be used as a correlative dating tool to provide sur-

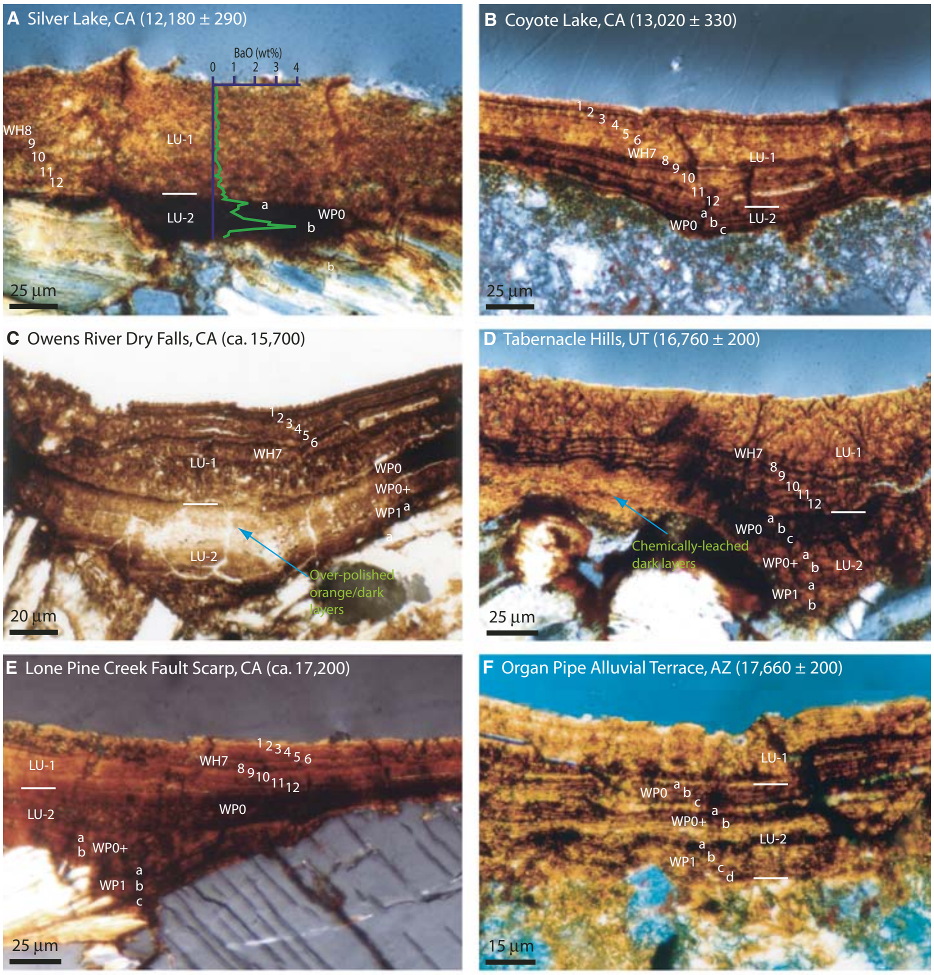

Figure 3. Varnish microstratigraphies from well-dated latest Pleistocene geomorphic features in western U.S. Radiometric dates (in calendar yr B.P.; Table 1) of these geomorphic features provide age constraints on initiation of basal varnish layers in microstratigraphies. Note that dark layer WP0 in A contains two Ba-rich peaks, as revealed by microprobe line profile analyses, corresponding to dark bands WP0a and WP0b in the generalized layering sequence (Fig. 2).

face exposure age estimates for geomorphic and geoarchaeological features (i.e., petroglyphs, geoglyphs, and stone artifacts) in the western U.S. drylands.

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